Chapter 5
Bench Systems

The test facility consists of all buildings, installations and systems within used for the test or in operational connection with the test (feed and purge lines, roof and court installations, for example). Examples of typical associated outbuildings are the control bunker, the fuel storage, the water tower and the steam generator of an altitude facility.

The engine test means an execution of an engineering process. Therefore the systems of the facility are classified according their relevance for test execution. There are systems for the process itself, for safety and for the building. The systems for the building (heating, air condition, lift etc.) are not part of the operational aspects of the facility. The safety aspects are only touched here where they have an impact on the process. The focus in this chapter is on the systems on the facility side which are directly needed for the test execution.

5.1 Principles for the Erection of a Test Facility

The main components of a test facility for a cryogenic rocket engine are the vessels for the fuel and for the oxidiser. These vessels are normally separated from each other and from the rocket engine by massive concrete walls (Fig. 5.1).

Remark 5.1 *During the erection of the facility **P5** at DLR in Lampoldshausen, in international cooperation the measures for a passage in a wall of 2 m thickness was misunderstood. In consequence the passage was at the wrong position and the prepared piping system had to be refabricated (Fig. 5.2).*

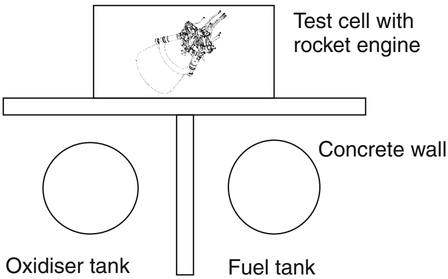

Fig. 5.1 Typical arrangement of the main components of a test facility (Photo: DLR)

W. Kitsche, *Operation of a Cryogenic Rocket Engine*, Springer Aerospace Technology,
DOI 10.1007/978-3-642-10565-4_5,

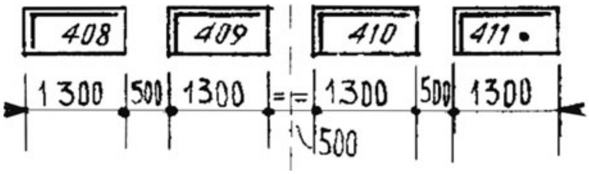

Fig. 5.2 Mistaken measurements. The French architects specified 500 mm between the two dots, the executing German company interpreted it as 2 × 500 mm because of the equality sign (Plan: SERETE)

5.2 Back Up Systems

The rocket engine as well as the test facility consists of several subsystems and components. In order to increase the reliability of the complete system important subsystems have a back up system.

Indispensable is a second computer system for control of the rocket engine. In case of a severe problem on the main computer during a hot run, and if the continuation of the test is not possible, a second computer has to be on stand-by to perform a proper abort of the test. An internal monitoring system of the computer (*watch dog*) watches all essential systems and functions of the computer, and switches the control automatically to the back up computer if one of the monitored functions is not provided any more (Table 5.1).

Indispensable as well is the electrical power. The total power supply of the test facility *P5* is about 800 kW (700 kW for the bench, 100 kW for the control building). Except for some very powerful consumers (e.g. water pump of 355 kW) all electrical consumers needed for the test are immune to a power failure. They are either connected to an *uninterrupted power supply* (e.g. the computer with 20 kW) where the power is taken from several battery chains or they are connected to a power stand-by unit driven by a *diesel* engine emergency backup generator. This engine and unit is started in case of power failure and runs up within 7 s.

Remark 5.2 *In former times computer systems had a much higher power consumption and heat release. Therefore the temperature in the computer room was also monitored, an air conditioning system (AC) having to maintain the correct temperature. The AC was able to transport a heat of 165 kW out of the control building, including its own electrical consumption of 45 kW. The AC also had an identical back up machine.*

Table 5.1 Back up power supply of the test facility *P5* at DLR in Lampoldshausen

Stand-by unit (Diesel engine)	NEA	398 KVA
Uninterrupted power supply	USV	3 × 60 KVA
For MCC and bench systems	230 V	3 × 62 Batteries
For engine valves	24 V	12 Batteries
For bench valves	60 V	2 × 13 Batteries

The principles regarding how to decide if a back up system is necessary or not are treated in Chap. 8. Another example for a backup function is the combination of sensor signals (see Sects. 4.4.3).

Remark 5.3 *The **Norsk Data** computer of the facility **P5** for the **Vulcain** engine merges all monitored systems and functions (e.g. power supply, internal data flow) into 12 collecting functions. After 4 years of test operation a failure occurred on this computer, a so-called **fugitive watchdog.** The failure message disappeared after some milliseconds. The message initiated correctly the immediate abort of the control of the facility. The back up computer checked the failure message in its cycle of 100 ms but found no failure message any more. Hence the back up did not take over control of the facility. It halted in its state like frozen. Thanks to god this did not occur in a hot run, because then the consequences would have been the exact opposite to a **frozen** test facility.*

5.3 Fuel and Oxidiser Supply

On many test facilities the rocket engine is tested in a manner of maximum analogy to the engine operation during flight *(static rocket system tests under rated and off design conditions)* [19]. In this case the run tanks of the test facility are dimensioned to provide fuel (and oxidiser) for a test time of 100–150% of the burning time during the flight. For testing cryogenic main engines that means the need of large run tanks (for example 600 m^3 and 200 m^3 for the *P5*). A fuel delivery by (road) tankers (Fig. 5.3) (up to 15 in the example above) with direct refilling of the run tanks would be a serious encumbrance to other facility activities. Ideal is the

Fig. 5.3 Trailer for liquid oxygen (Photo: DLR)

Fig. 5.4 Discharge of a LH_2 trailer (Photo: DLR)

reception of the (road) tankers at an intermediate storage (Fig. 5.4) and transfer of the cryogenic fluids from there into the run tanks. During the test periods the run tanks are regularly refilled, pressurised for the test, almost emptied in the hot run and again depressurised. Chill down and warm up means a cycle of thermal load applied to a tank which consumes its life time. Therefore complete discharging of the tanks is avoided in order not to warm up the inner jacket of the double-walled tanks and not to have more and more cycles of thermal load (Fig. 5.3).

5.3.1 Vacuum Insulation

All mentioned vessels and tubes are vacuum insulated, that means a double-walled tank or tube and the space between inner and outer tank (tube) is evacuated (e.g. at 10^{-4} mbar) (Fig. 5.5). This method is accepted as the best passive insulation and is typical of the test facility but for weight reasons rarely used on the launcher. The status of the vacuum sections has to be checked frequently and has to be corrected where necessary. A lack of insulation would deteriorate the chill down behaviour of the facility and the engine and could impede the reaching of the chill down criteria. The line between the run tank and the rocket engine has several (vacuum) sections. The evacuation of one section takes several hours. The inner tube normally has many sensors (for pressure, temperature, mass flow or vibration) but the vacuum section has no sensor. The best vacuum check is the on site inspection directly after the test. Experienced staff can identify by the condensed water (or even icing) on the line the status of the vacuum section. To recover the vacuum of a section is very time consuming, the section is connected to a turbo molecular pump; at first the connecting tube is evacuated and then, after hours of pumping, the vacuum section itself. The evacuation can last for days if the section is not at ambient temperature and even longer if humidity has ingressed. The ingress of humidity is absolutely to be

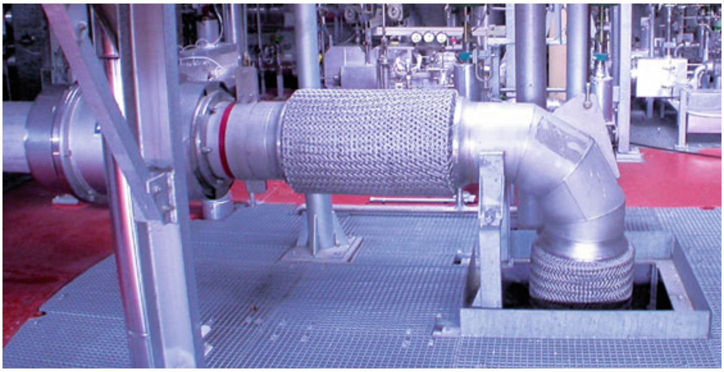

Fig. 5.5 Double walled LH_2 line with wire net protected compensators (Photo: DLR)

prevented and where appropriate the temperature of the section has to be increased with heating tapes.

The alternative to the evacuation is a filling of the section with carbon dioxide at ambient temperature. During the chill down of the inner tube the carbon dioxide transforms to dry ice and the pressure in the section decreases to some hundred mbar. This insulation method is not favourable on vertical lines. The gas would turn to ice, concentrate at the bottom of the section and create a bridge for heat conduction between inner and outer tube.

Remark 5.4 *Normally nitrogen is used to vent a vacuum section. A nitrogen gas bottle is connected to the section and it is vented slowly until the inside pressure has reached ambient pressure. By doing so a sudden increase is avoided and, much more important, no moisture can ingress the section. After many years of positive experience with this method a vacuum section of a partially filled hydrogen tank vas vented. The operator noticed with astonishment that the pressure in the section barely increased during venting. Doubtful, he asked for confirmation of the volume of the vacuum section. It became clear to the responsible engineer that the gaseous nitrogen in the section must have turned into ice and he gave the instruction to apply helium gas for venting. This instruction led to the next surprise for the operator. The helium remained gaseous and increased the pressure of the vacuum section rapidly. With a loud bang the pressure burst the disc which was installed on the section for safety reason (Figs. 5.6 and 5.7).*

5.3.2 Feed System

The feeding of fuel (or oxidiser) to the combustion chamber is mainly done by the turbo pump of the rocket engine itself. For proper performance of the pump the pressure at the pump inlet has to maintain a defined value above the requested *net positive suction head* (NPSH). For that purpose and to perform the chill down before the hot run, the test facility has a pressurisation system connected to the run tanks.

Fig. 5.6 Inner and outer flange of a double walled feed line (Photo: DLR)

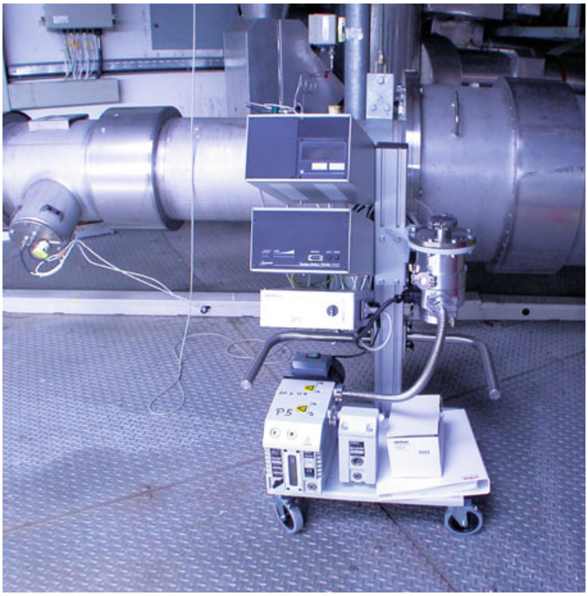

Fig. 5.7 Vacuum pump stand with turbo molecular pump (*left*) and rotary vane pump (*right*) (Photo: DLR)

It is a powerful system with enough capacity to replace within the test duration the whole cryogenic fluid in the tanks by an adequate gas. On the facility *P5*, hydrogen gas is used to pressurise the hydrogen tank and nitrogen gas to pressurise the oxygen tank. These gases are stored at high pressure (e.g. 250 bar) and are reduced stepwise to low pressure (e.g. 3 bar) to float at last the run tank. Depending on the pressurisation mode and purpose heat introduction, evaporation of the liquids or condensation of the gas (see Appendix H) has to be considered. The pressurisation during the relative long chill down phase can create a more or less distinct layering of temperatures. The temperature deviation from the mean value is indeed only a few tenths of a degree but it can be decisive for the shut-down of the engine.

Remark 5.5 *For the first filling of the hydrogen feed line on the **P5** with liquid hydrogen, the test team pressurised the run tank and opened the valves towards a hydraulic dummy which simulated the rocket engine. It was assumed to be a simple calculation to find out what pressure in the tank would push the fluid through a standpipe to the inlet of the feed line. The test leader stopped the pressurisation when the calculated pressure was reached. But the temperature at the inlet of the feed line did not indicate any presence of a cryogenic fluid. Hence the pressure was raised in steps of 0.1 bar. For the sensors and the measurement chains it was the first time to measure the low temperature of the fluid, and it was uncertain that both worked without failure. After several steps of pressure increase the temperature dropped drastically and the typical 20 K of liquid hydrogen was indicated. Afterwards we figured out that a small amount of liquid at the inlet instantly evaporates and a remarkable counter pressure is created which pushes the liquid back into the tank. This evaporation creates a pressure oscillation in the feed line during the first phase of the chill down. The amplitude of this oscillation is of the order of the mean pressure value in the feed line. The phenomenon is treated in the literature as the **surge** effect. It can also occur on a launcher and has to be treated there with much more attention because the flight line is far more fragile than the bench line (Fig. 5.8).*

First attempts to compute the pressure oscillation in the feed line were made by the author in 1994 (Fig. 5.9). The feed system was modelled in one dimension of

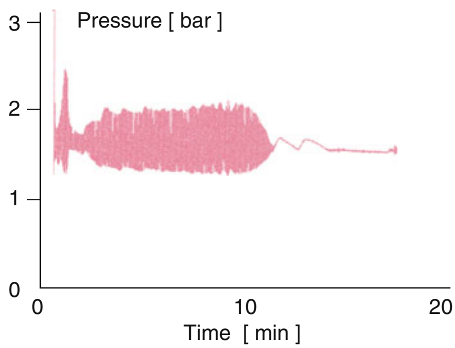

Fig. 5.8 Pressure oscillation in the hydrogen feed line during the first phase of the chill down (Photo: DLR)

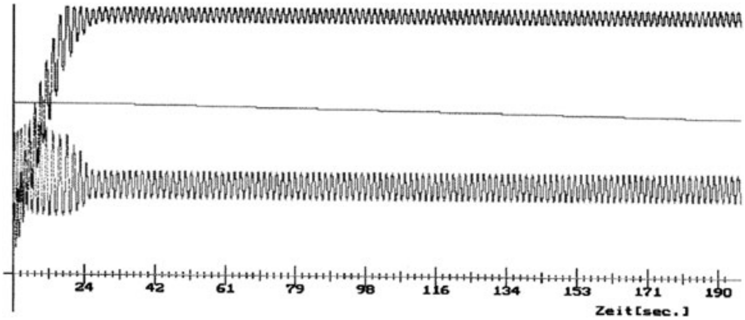

Fig. 5.9 Early computation of the first phase of a chill down pressure (*bottom*) and filling level (*top*) of a hydrogen feed line vs time (ScreenShot: DLR)

space and in time (unsteady). The physics of the model is described by a system of ordinary differential equations (ODE) and was computed by means of the *Kutta-Runge* algorithm. The results were in sufficient agreement with a good part of the measurements and with the principle behaviour of the system.

The transient behaviour has essential importance for all liquid space propulsion systems. Therefore the ESA supported a program to develop a software library for computation of various processes in fluid systems of spacecrafts. [13]

Remark 5.6 *The test facility P8 for the development of high pressure combustion chambers at DLR in Lampoldshausen reaches at the interface bench/specimen a maximum pressure of 320 bar. Because the specimens have no turbo pumps, the enormous pressure has to be created by pressurisation of the run tanks. The tanks have an internal shield which prevents an injection of the gas into the cryogenic fluid. The first attempts at pressurisation failed because the velocity of the gas was too high and its energy dissipated. The temperature of the fluid increased to an undesirably high level but the pressure could not be increased sufficiently. The test leader developed a* ***parabolic*** *pressurisation in which the pressure in the tank was increased within 1 min along a parabolic profile from 1 to 500 bar.*

5.4 Measurement, Control and Command (MCC) Systems

The need for precise test execution, monitoring of important parameters and exact measurement is as old as rocket engine testing. The test engineers of the past always applied the available state of the art in technique for this purpose. Nowadays these tasks are done by a *measurement, control and command (MCC)* system (Fig. 5.10). It normally consists of a system of computers, storage devices and a periphery as the interface to the facility and engine and for operator work at terminals. Meanwhile the MCC is not only applied for the hot run but also for test preparation and for the reset of the facility after test.

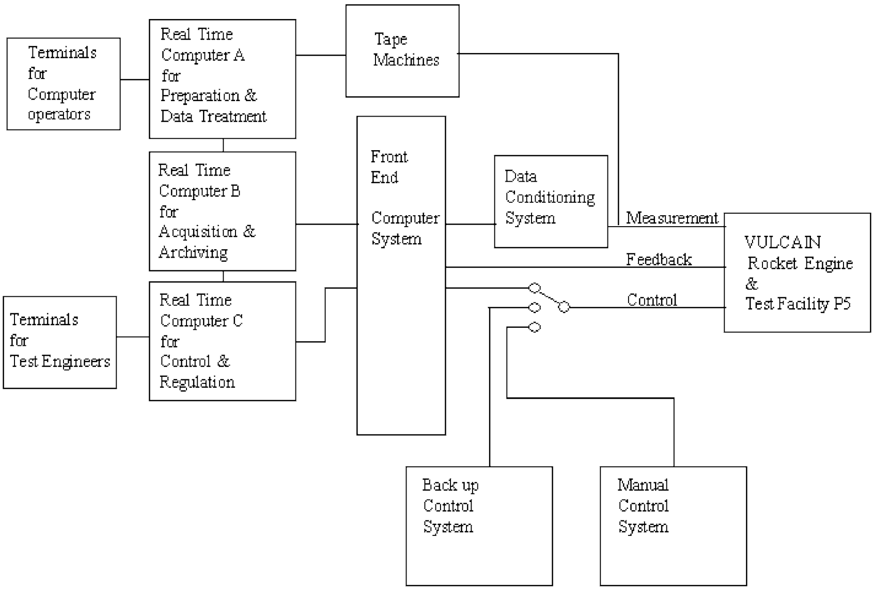

Fig. 5.10 Original MCC system of the facility *P5* (Photo: DLR)

5.4.1 Historical Review

In the first test facilities for rocket engines the piping went through the control room. The test engineers adjusted the pressure reducers and regulation valves manually and read off the values from pressure gauges. The bench and the specimen were observed through a slot in a concrete wall or through a periscope.

Remark 5.7 *The pioneers of rocket engine testing only had a small fraction of today's control systems. Mostly they applied the principle of starting a pre-adjusted engine and running it in one operational point without any variation up to the shutdown. The second generation of test engineers corrected a valve position from a safe distance by means of cords. To the amazement of the scholar of the old school, a perfect mixture ratio levelled out during the hot run.*

Due to the development of electronics and sensors in the 1960s and 1970s more and more non-electrical measurements were transformed and displayed on analogue gauges. The control room of a test facility of those days was dominated by this kind of instrument (Fig. 5.11).

Each engineer of the test team watched about four gauges and informed the test leader in cases of reaching a critical value; then the test leader decided for test abortion or continuation. The sight to the engine was still through the bulletproof glass in the slots of the bunker wall. By and by the monitors entered the control rooms of the test facilities. At first they were used to display pictures from cameras. Parallel with the development of the computer, the display of data on a screen entered the control

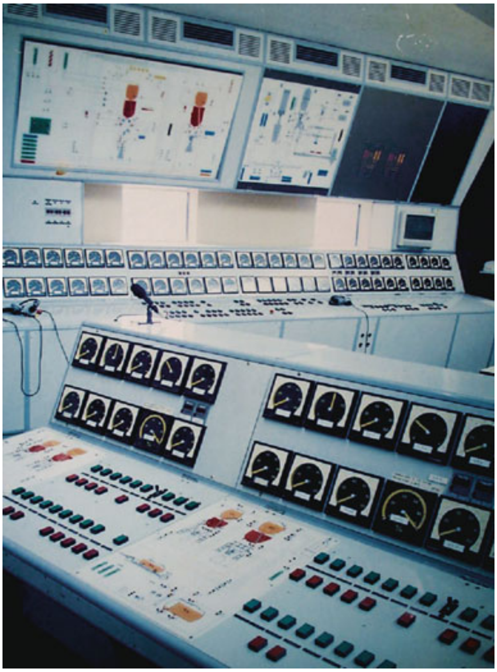

Fig. 5.11 Control room of the test facility *P4* for the *Viking* engine (1970s) (Photo: DLR)

systems. The arrays of desks as in the NASA control centre in Houston became the standard control technique for space application (Figs. 5.12 and 5.13).

In the 1980s the available electronics and display components were consequently applied. Remote controlled cameras transmitted high quality coloured pictures to several monitors in the control room. All valves and pressure reducers necessary for test guidance were remote controlled from a switch board of several metres width. Special monitors with *light pens* provided all the required measurement values in a displayed piping synoptic. The computer allowed a higher degree of automation. In the 1970s the computer only controlled the hot run but in the 1980s the test

Fig. 5.12 NASA control centre in Houston during the *Apollo* program (1960s) (Website: NASA)

Fig. 5.13 Control room of the facility *P5* for the *Vulcain* engine DLR, Lampoldshausen (1980s) (Photo: DLR)

preparation was also performed with computer support. The test engineer no longer actuated a remote controlled valve; instead he entered a command via the keyboard of his terminal and started a complex sequence of valve activations. In the 1980s each valve and sensor still had its own cabling between the test bench and the control bunker.

In the 1990s the large switch boards disappeared from the control rooms and the desks were replaced by normal tables with standard monitors and keyboards. These terminals were connected to large computers still with the structure of the old main frame computer. The extensive cabling between control building and test bench was drastically reduced by the application of intelligent systems on the facility. These systems processed the measured signals and transferred digital data in collective lines to the MCC in the control bunker.

The computers of the current MCC systems have the structure of a workstation and the acquisition of data is via high frequency signals converted to digital format, no longer analogue on magnetic tapes (Fig. 5.14).

5.4.2 Control Programs

In the 1970s the control based on fix electronic hardware components was replaced by programmable logic controllers (PLC). In the beginning only digital inputs and outputs were available, which were read and set in a cycle. The number of inputs and

Fig. 5.14 Control room of a test facility in the 1990s (Photo: DLR)

outputs was extendable with modules and thereby the number of channels was high enough even for complex facilities. The cycling time (e.g. 2.5 ms) was also short enough to control even fast processes. The processing of analogue signals (e.g. limit switches) had to be realised by additional, special components. Later generations of these control units became more powerful and were also able to perform regulation processes.

Remark 5.8 *The DLR applied the PLC (a Procontic by BBC) on small test facilities until 1997. Besides the Procontic, more and more* ***Siemens*** *computer were installed (S3, S5 and S7) (Fig. 5.15).*

The typical computer for control of a test facility in the 1980s was a *main frame computer* or a set of *main frame computers*. This kind of computer runs programs of different categories. The basic is an operating system, and on top of this we have the utilities to operate the computer (*software and hardware*). For the control (including regulation and monitoring) of the rocket engine and test facility, another category of programs was applied, the sequences.

A sequence contains a number of statements which are sequentially processed. A good part of the statements is standard in any program language (mathematical operations, loops, subroutine calls etc.); further on there are statements for the dialog with the periphery of the control computer. Their purpose is to switch a valve, activate a system, read a sensor signal, release a reference value etc. The program language in the 1980s was a derivative from FORTRAN; in 2008 it was rather like PASCAL. Figure 5.16 shows a loop from a purging sequence which opens/closes valves with defined waiting times in between.

An example of a simple use of a sequence is the testing of valves. Selected valves are opened/closed by the sequence in a defined timing. In parallel the position feed back from the valves is recorded. The evaluation means a study of opening/closing duration of the valves.

On a test day, between 70 and 80 sequences are applied, partially in parallel, partially in series. The sequences used make up a structured system (Fig. 5.17); they

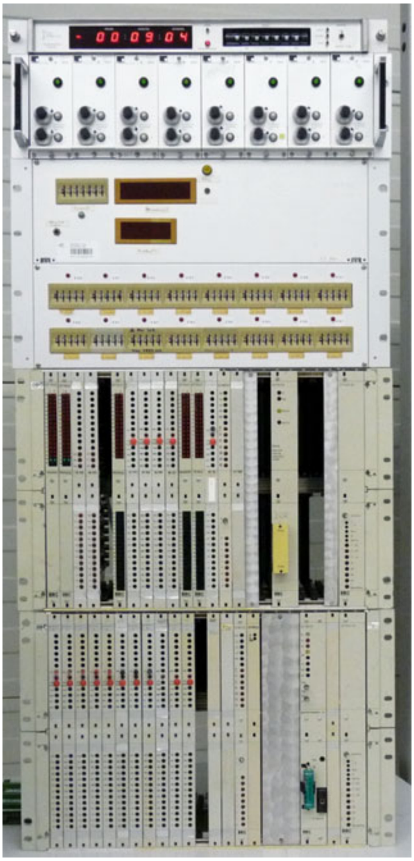

Fig. 5.15 Programmable logic controller, BBC (Photo: DLR)

have different priorities and a specific task. Sequences can start and stop each other, there are conditioned and unconditioned activations of sequences and they can enter a stand-by state. The name of the sequence contains significant information about its priority, the controlled area and the task of the sequence. The sequence named

```
COMPUTE COUNTER = 0
DO
   EXIT ON COUNTER > 9
   SWITCHOFF AVY250,0,ACTION=ALARM
   WAIT DELAY = 40S
   SWITCHOFF AVY126,0,ACTION=ALARM
   WAIT DELAY = 20S
   SWITCHON AVY250,0,ACTION=ALARM
   WAIT DELAY = 40S
   COMPUTE COUNTER = COUNTER + 1
   MESSAGE 3,1,1001,COUNTER
   SWITCHON AVY126,0,ACTION=ALARM
ENDDO
```

```
for I := 1 to 10 do
            AVY250(FALSE);
            SeqWaitTime(T#40s);
            AVY126(FALSE);
            SeqWaitTime(T#20s);
            AVY250(TRUE);
            SeqWaitTime(T#40s);
            LogMsgCon1 := CONCAT("-I- ",(I));
            LogMsgTxt := CONCAT(LogMsgCon1,".
Bedrueckung LH2 mit GHe!");
            ILogMsg(0,GetCallers(),LogMsgTxt);
            AVY126(TRUE);
end_for;
```

Fig. 5.16 (**a**) Part of a sequence 1988. (**b**) Part of a sequence 2008 (Sequence: DLR)

Phase (chronological order)	Main-Sequenz	Sub-Sequence				
Automatic Sequence (H0-5')	NETSTDQA	NETSTPRP (NETSTPR1)	NZLDEBCD			
			NEPRPRLS			
			NZPARDIS			
		NETSTSTA (NETSTST1)	NESTARLS			
			NEBUBO2M			
			NHDISPH2			
			NODISPOX			
			NEPCSA5S (Gimballing)	UECHDEND	NHPURTPH	NHPURLH2
						NHSMOTPH
						NHPURVAH
					NOPURTPO	NOPURRIE
						NOSMOTPO
						NOPURVAO
			NESCPOFG			
			NEABOSTA	NZCHDCRT		
			UEWATOFF	NEABOSTA	NZCHDCRT	
			UEENGSDN	NZBCC1		
				NZBCC2		
				NZBCC3		
				NZBCC4		
				UEENGRLO	UEBENRLO	
				UEAKRBUT		
				NETSTEND	NHDISPH2	
					NODISPOX	
					NHPURTPH	NHPURLH2
						NHSMOTPH
						NHPURVAH
					NOPURTPO	NOPURRIE
						NOSMOTPO
						NOPURVAO
					NZNAOFF	
		NEENGMON	NEGIMBAL			
			NEENGREC			
Hot run (H0)		NEENGSTA (NEENGST1)	[NZBCC8]			
			[NZBCC9]			
			[NZRHOLOH]			
			NEH02PFX			
			NEH02PFY			
			NEEVPPO			
			NEEVPPH			
			NEEVPPHB			
			NEENGREG	NZRHOLOH		
				NZREGMAN		
Shut-down (H2)			UEENGSDN	NZBCC1		
				NZBCC2		
				NZBCC4		
				UEENGRLO	UEBENRLO	
				UEAKRBUT		
				NETSTEND	NHDISPH2	
					NODISPOX	

Fig. 5.17 List of sequences for a *Vulcain*-Test (without chill down and reset phase) (Photo: DLR)

NHPURLH2, for example, has a **N**ormal priority, controls the **H**ydrogen area and has to **PUR**ge the **LH2** area.

Often a sequence is executed in dialog to the test team. The sequence, for example, offers the responsible operator a prolongation of the chill down phase of a segment. Due to this the operator can synchronise his process to other processes on the facility. The most drastic external influence comes from the *red button* of the test leader desk. This button releases immediately a pre-selected shut-down of the rocket engine and a transient of the facility into the safe state.

The *hot run sequence* has a central function within all test sequences. While this sequence is executed no intervention from the test team is possible (except via the red button). For control of the hot run the precision of control signals is of particular importance. In this phase precision cannot be taken for granted because, especially here, the signals are close-packed. For the release of a control command

in the 1980s a maximum delay of 10 ms was allowed. Depending on the type of command the computer took up to 6 ms to execute it. If several commands were released at the same time (e.g. during start up or shut-down) the delay of the last command increased to values longer than 10 ms. But for many systems (and for valves) this was still acceptable because the reaction time of these systems itself was generally more than one order of magnitude higher (see Remarks 3.2 and 3.3).

5.4.3 Engine Control

The standard control element on a rocket engine is the pneumatic open/close valve (e.g. before the combustion chamber). The pneumatic actuator is driven by an inert gas (e.g. helium) and the open/close chambers are pressurised/depressurised via electromagnetic valves (pilot valves). The electrical activation of the pilot valves comes originally from the MCC system of the facility (see Appendix M). For hydraulic valves (e.g. thrust vector control) the same principle is applied but they have the advantage that arbitrary valve positions between minimum and maximum are adjustable. Normally each valve has a feed back of its position which is read as a digital input (for regulation valves as an analogous input) by the MCC system. The pyrotechnical elements to ignite the engine are themselves ignited by initiators (a pill of powder) which are ignited electrically. These electrical igniter circuits are also activated by the MCC system authorised by key switches. By the coordinated actions of all control elements and the commands of the MCC all functions of the rocket engine are controlled (start up, switch off, regulation, thrust vector adjustment, ground-to-flight switch over etc.). The commands for the control elements are released periodically with a precision of ${}^{-0}_{+10}ms$. The MCC system of the facility for the *Vulcain* tests had three linked computers each with several processing units. The periphery of the MCC system has interfaces for the engine and facility control, for data acquisition and recording and the terminals to operate the total facility (MCC system, test bench and engine) (Table 5.2).

Table 5.2 Input and output channels (bench and engine) of the MCC system of the facility *P5*

Input channels	Number
Analog	608
Impulse counter	10
Digital	2048
HF data (20 kHz)	96
Output channels	
Analog	10
Digital	512

5.4.4 Data Acquisition

The analogous signals from the sensors are transmitted via measurement chains (see Appendix L) to a *signal conditioning system* and forwarded to the A/D converters

in the periphery of the computer. The signal conditioning system is a number of amplifier racks where the signal of the sensor is adapted to the input of the computer. The MCC system controls and, respectively, sets the amplification and offset of the sensor signal in the conditioning system. Internally the computer stores a raw value of the measurement and computes according to a polynomial the physical value of the measurement. The power supply of the sensor (see Appendix K) is also located within the signal conditioning system. The long way of the cabling between signal conditioning (in the control bunker) and the sensor (on the facility or engine) induces a drop of voltage. Therefore, beside the original measurement signal, the voltage at the sensor is also measured via a sense line. Altogether a total of six wires are needed for one sensor (measurement, sense and supply circuit). Most of the sensors measure pressures or temperatures on the facility or rocket engine; other measured physical parameters are vibrations, forces, deformations and shaft speeds (Fig. 5.18).

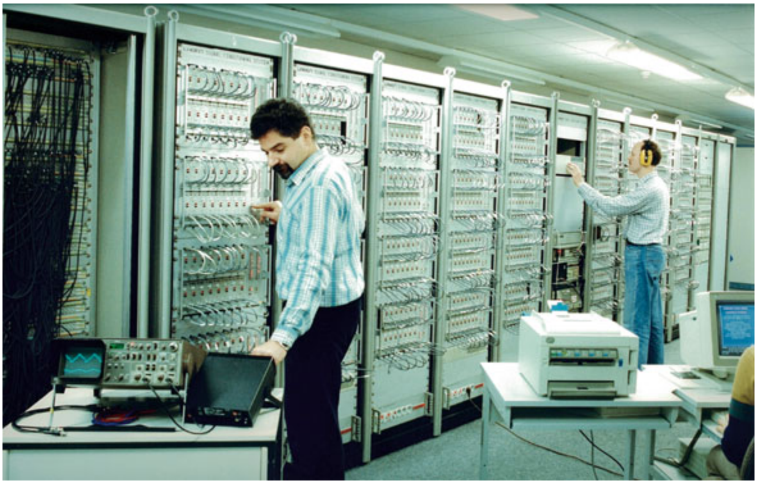

Fig. 5.18 Signal conditioning system (amplifier racks) (Photo: DLR)

5.4.5 Measurement Validation

The acquired raw data are very seldom directly used for regulation or for the monitoring of parameters. The data for such a purpose go through a validation process. A typical validation of data for regulation of the *Vulcain engine* is the following process:

1. Computation of the mean value of the last five acquired values
2. Exclusion of all values that differ more than 20% from the mean value
3. Computation of the mean value of the remaining values

4. Selection of the first mean value in cases of exclusion of all values (see 2 above), and selection of the second mean value if no more than four values were excluded

Remark 5.9 *Among the aerospace systems since the 1970s, electronic regulation units have displaced more and more mechanic/hydraulic regulation units. Until then the non-electrical parameters were boosted hydraulically or mechanically and then directly used for control purpose. If electronic units are used the non-electric parameters are converted by sensors into an electrical signal, the regulation unit reads the signal, processes it and sends another electrical signal to electric/mechanic actuators. The standard signal interface in the 1970s was the* ***V24 interface****. In this regulation the engine engineers had to face, for the first time, the problem of* ***non-physical measurement values****. A regulation which completely relied on the correctness of the used signals caused unwanted shut offs and regulation failures. The reason was a disturbance of the signal, often only for very short times (****peaks****). It duped a violation of a limit concerning a critical engine parameter to the regulation unit. This kind of error can be reduced by improvement of the hardware or (more favourably) by improvement of the programming of the regulation algorithm (measurement validation).*

5.5 Detection Systems

While a test facility is operational its vessels are permanently filled with fuel, oxidiser and complementary fluids. To avoid a warm up the vessels for the cryogenic fluids are not completely emptied in a test. The complementary fluids are partially stored at high pressure (e.g. 300 bar). The risk of a leak in a vessel or in the piping cannot be excluded completely. Therefore the facility is equipped with gas detectors around the tanks and in all rooms where pipes are routed. In the case of a gas leakage or displacement of air the detectors linked to a monitoring system will automatically set off an alarm. In addition to these gas detectors the system is equipped with differential heat sensors. The close surroundings of the rocket engine is monitored with two gas analyser systems, each working on another physical principle (e.g. oxygen-reduction-reaction, see Appendix N).

Inside the rocket engine further gas concentration measurements are taken. They reveal a possible internal leak during the chill down phase. The gas samples are taken with *Teflon* hoses which burn off after ignition.

Large test facilities are evacuated before authorisation to open the main valves is given. Because from that moment on no personnel are present on the facility, all systems have to be not only remotely controlled but also remotely monitored. Besides monitoring by detectors, monitoring by cameras is also very important. Events which cannot be sensed by the detectors might still be visible on the video monitors in the control room.

The risk of the presence of hydrogen or oxygen due to an internal leak inside the lines is minimised during the non-active phases of the bench by a safety pressurisation of the lines with inert gas.

The correct function of this pressurisation and the tank pressure are monitored in non-active phases. A failure initiates an alarm and releases the organised communication of the responsible operators.

5.6 Test Cell Systems

The test cell houses the rocket engine in its test position. During the hot run it is wide open, that is the large lid of the exhaust guiding system is removed, the wide lateral gates are opened and the armour plated doors to the other rooms of the test bench are closed. The device to move the large lid and the wide gates are test cell systems, the schedule of the test day directly depending on their correct function. The thrust frame which bears the engine forces is another system of the test cell; it is a heavy, massive steel construction which is anchored in the concrete structure of the bench.

Between the engine and the inlet of the exhaust guiding system, three pilot burners are installed (Fig. 5.19). Their purpose is to ignite hydrogen which enters the test cell from the moment the chamber valve is opened. Without these burners the hydrogen would ignite with the engine ignition and the detonating gas would burn

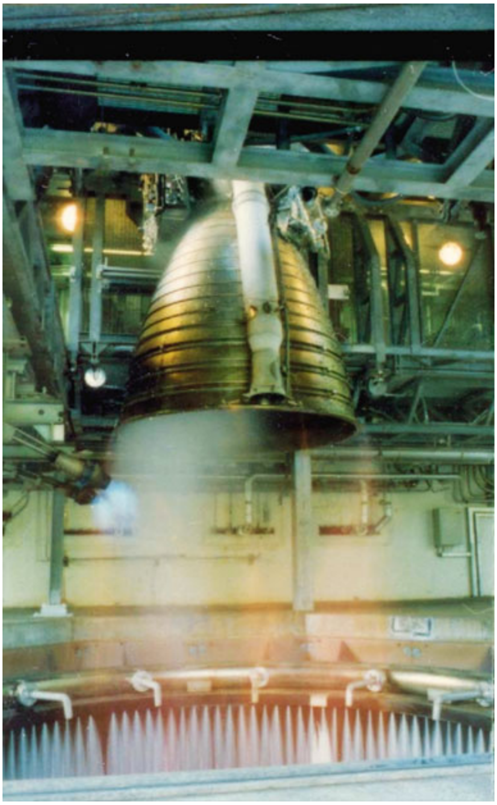

Fig. 5.19 Test cell with running pilot burners and cooling water supply, in between the torus with angled nozzles for creation of an ejector jet(Photo: DLR)

around the engine where cables and insulation material could be affected. These pilot ignition systems are typical for cryogenic engines: a gas flame (for the *Vulcain*) or a spark providing device (e.g. for the *Space Shuttle Main Engine*) is used for that purpose. Another test cell system inhibits the climb up of the burnt gas, a suction system running on an ejector jet at the inlet of the exhaust guiding duct and a curtain like jet around the engine creating a downward flow into the wide duct.

5.7 Exhaust System

In its nominal operational point the *Vulcain* converts more than 3 GW chemical power into thermal power. All structures and systems in the vicinity of the exhaust jet have to be adequately protected from this thermal load. The launch table for the rocket has to bear this load for less than 10 s and it is sufficient to cover the concerned area with a water layer. On the test facility the exhaust jet has to be guided away from the facility and the area concerned is loaded with the thermal power of the exhaust jet for several minutes. Test facilities erected on a hillside with enough depth below the engine have the advantage that the jet can blow onto the surface at the bottom (Fig. 5.20).

Fig. 5.20 Test facility without exhaust guiding system, test stand 1A at air force research laboratory in Edwards, USA (Website: US Air Force)

A guiding system is necessary if the exhaust jet has to be led away from the facility. A large duct guides and deflects the jet. Such a system is made of ordinary steel and definitely needs a cooling system (Figs. 5.21–5.23).

The hillside position of a facility is also an advantage for the design of the cooling water supply of an exhaust guiding system. The system is fed by water towers which are erected at a higher geodetic point than the facility. Due to the hydrostatic pressure the installation of water pumps of high power can be at least partially reduced.

Remark 5.10 *The cooling water flow for the **Vulcain*** ($P_{thermal} = 3,3\,\text{GW}$) *was 2,000 L/s, 46% of the amount evaporated. The higher power of the **Vulcain 2** required an increase to 2,750 L/s and a significant higher fraction evaporated.*

*The exhaust guiding system of the facility **P5** including its cooling water supply was the biggest permanent challenge in the operation of this facility. After each test, an inspection and normally small repairs are necessary.*

At the beginning of the test periods the water distribution was optimised. Enough water has to be present everywhere; on the other hand, too much water causes a partial blocking of the duct.

*During one of the first **Vulcain 2** tests an upper segment of the system fused and, during the first long duration tests of the **Vulcain**, soak water was rejected from the upper segment into the test cell. The water hindered the sight to the engine and*

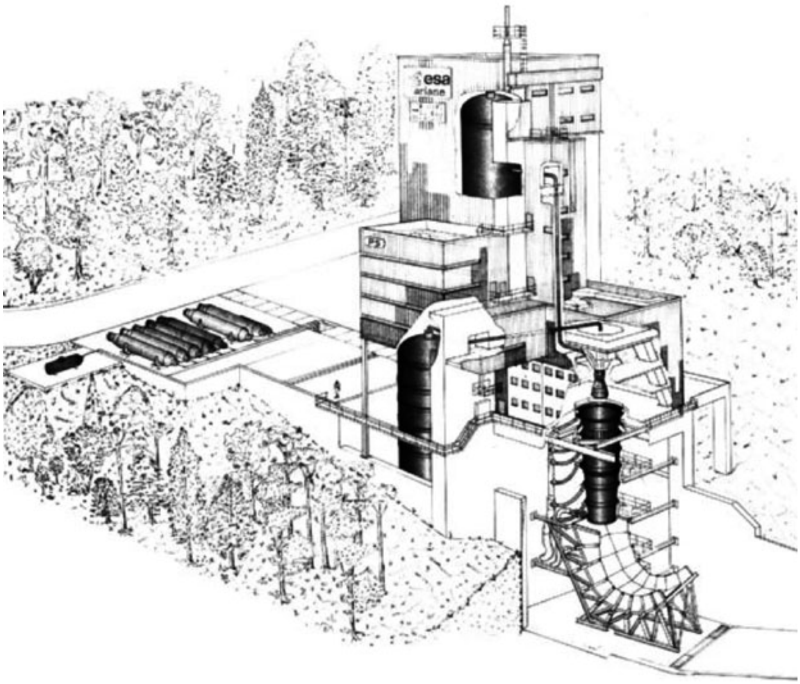

Fig. 5.21 Test facility with exhaust guiding system, facility *P5* at DLR in Lampoldshausen (Photo: DLR)

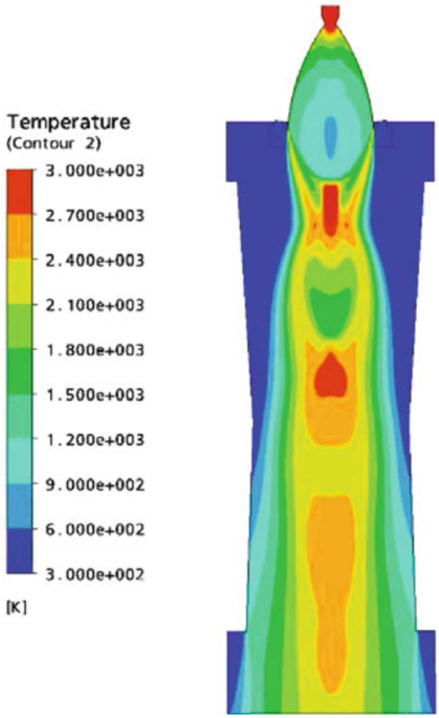

Fig. 5.22 Typical temperature distribution in an exhaust guiding system (Screen Shot: DLR)

another severe problem emerged, the soak water also reached the nozzle; it caused a partial cooling of the nozzle, the water was evaporated and the nozzle returned again to its expected temperature. This could happen several times in one hot run and the nozzle designer had to take each of these events as a hot run cycle of the nozzle. Due to that fact the life time of the nozzle was drastically reduced.

The exhaust guiding system has to withstand the highest load when the thrust vector control of the engine is applied during a hot run. The oblique exhaust jet

Fig. 5.23 Flow check of the exhaust cooling system (Photo: DLR)

of the gimballed engine hits the inner surface of the guide tube. In order to avoid melting of the steel it can only be pointed at the same spot for a short time.

5.8 Altitude Simulation

Upper stage engines are started and operated during a flight phase at high altitude. The conditions of these altitudes, in particular the low pressure, are simulated in test facilities with vacuum chambers. The test cell of such a facility is designed to be evacuated and the pressure can be lowered to some mbar. But the low pressure also has to be maintained during engine operation and therefore a suction system is required to suck off the complete engine exhaust. The vacuum chamber and the suction system upgrade the test facility to an *altitude facility* in which upper stage engines can be adequately validated for their mission. The vacuum in the test cell before ignition can be established slowly by means of pumps, but for engine operation a more powerful system is necessary. The exhaust jet of normal upper stage engines (e.g. as for the *Ariane 5*) are sucked off by ejectors. They work on the same principle as the water jet pump (see Appendix I). The jet of the ejector is created by combustion of a fuel/oxidiser mixture at high pressure and addition of water (steam generator). Except for the water injection the steam generator is in principle a rocket combustion chamber working at considerable pressure and temperature. The created steam jet is used to operate the ejector and, respectively, to suck off the engine exhaust. To obtain a sufficiently low pressure the facility has multiple stages (Table 5.3). The steam is back liquefied in a giant condenser by injection of cold water and collected in an underground water basin. The diffuser below the engine and the following duct of the exhaust and ejector jet is a highly interesting subject of gas dynamics but still the design can only be realised successful in an accurate development with fundamental experience. The reason for the complexity of this flow are the effects of phase and heat transition, the different *Mach* number regions, turbulence, boundary layer effects and the still ongoing chemical reaction. Hence the prediction of the flow and the calculation of the overall performance of the altitude facility is an ambitious subject. The altitude facility including its steam generators (Fig. 5.24 does not show the five steam generators of the facility) is an enormous increase of the complexity of the overall test facility. In principle a second facility

Table 5.3 Performance of the steam generators for the altitude facility *P4.1* at DLR in Lampoldshausen

Steam generator	Ejector	Mass flow	Steam pressure	Operational time
1	1	55 kg/s	20 bar	15 min
2	1	55 kg/s	20 bar	15 min
3	2	58 kg/s	20 bar	15 min
4	2	58 kg/s	20 bar	15 min
5	Chill down ejector	10 kg/s	20 bar	25 min

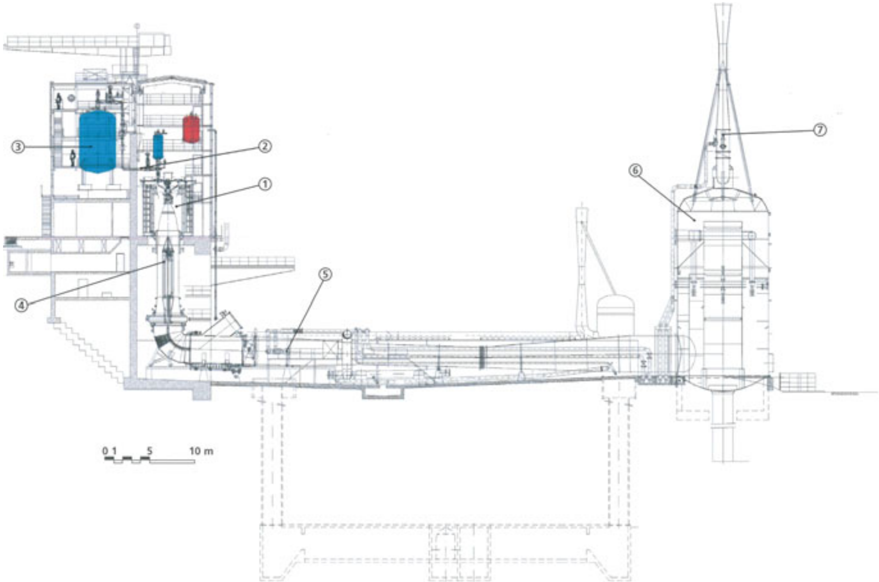

Fig. 5.24 Altitude facility *P4.1* at DLR in Lampoldshausen for the development of the *Vinci* engine under altitude condition (Photo: DLR)

is operated which is to be adjusted precisely at its interface to the rocket engine in the test cell.

On facilities for a small thruster (e.g. 10 N) the vacuum test chamber can be kept at low pressure (1–30 mbar) by means of big vessels (e.g. 500 m^3). The vessels are evacuated by Roots pumps and rotary vane pumps. Pump operation during a firing test maintains the vacuum which means that the test duration is not limited by the facility. Such a facility can also be used for short duration tests (e.g. 20 s) of small engines of some hundred Newton of force.

Another alternative is the operation of ejectors with steam created before the test and stored in vessels.